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STUDIES OF SATELLITE AND PLANETARY SURFACES AND ATMOSPHERES

September 1, 1977 - August 31, 1978

Principal Investigator: Professor Carl Sagan

CORNELL UNIVERSITY


Laboratory for Planetary Studies

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Carl Sagan
Principal Investigator

APPENDIX I

Summaries of research supported by NASA Grant NGR 33-010-082 completed or published since the last annual report are listed below.

(1) "Limb-Darkening and the Structure of the Jovian Atmosphere," William I. Newman and Carl Sagan, Icarus, in press, Abstract in Bull. Amer. Astron. Soc., 9, 534,

By observing the transit of various cloud features across the Jovian disk, Terrile and Westphal (1977) have constructed limb-darkening curves for three regions in the 4.6 to 5.1 μm band. Several models currently employed in describing the radiative or dynamical properties of planetary atmospheres are here examined to understand their implications for limb-darkening. The statistical problem of fitting these models to the observed data is reviewed and methods for applying multiple regression analysis are discussed. Analysis of variance techniques are introduced to test the viability of a given physical process as a cause of the observed limb-darkening.

The intermediate flux region of the North Equatorial Belt appears to be in only modest departure from radiative equilibrium. The limb-darkening curve for the South Temperate Belt is rich in structure and cannot be satisfactorily ascribed to any single physical mechanism; a combination of several, as yet unidentified, processes is likely involved. The hottest area of the North and South Equatorial Belts exhibit limb-darkening curves that are typical of atmospheres in convective equilibrium. In this case, we derive a measure of the departure of the lapse rate from

the dry adiabatic value ($n \approx 1.68$), which furnishes strong evidence for a phase transition at unit optical depth in the NEB and SEB. Although the system $\text{NH}_3\text{-H}_2\text{S}$ cannot be entirely ruled out, the freezing of an aqueous ammonia solution is shown to be consistent with the parameter fit and solar abundance data, while being in close agreement with Lewis' (1969a) cloud models.

(2) "The Application of Generalized Inverse Theory to the Recovery of Temperature Profiles," W.I. Newman, Journal of the Atmospheric Sciences, in press.

The recovery of temperature profiles by generalized inverse theory is examined. The spectral expansion or minimum information method is shown to eliminate some of the deficiencies of the Backus-Gilbert method.

(3) "Models for the Reflection Spectrum of Jupiter's North Equatorial Belt," K. Rages and Carl Sagan, Icarus, in press.

The reflection spectra of model jovian atmospheres containing red chromophore particles mixed in a Rayleigh layer, surmounting a high albedo cloud, are calculated for two candidate chromophores: orthorhombic sulfur and the brown photochemically produced organic polymer of Khare and Sagan. Comparison with Orton's spectrophotometry of the North Equatorial Belt shows that sulfur alone cannot explain the observations, but that the reflection spectrum can be satisfactorily reproduced by a chromophore consisting of about 90 percent sulfur plus about 10 percent complex organic

molecules in particles roughly one micron in radius. This particle size is consistent with hydrodynamic constraints arising from the time for pyrolytic decomposition of the chromophore, and also with polarization estimates. The precipitable thickness of chromophore in the line of sight is about $3 \times 10^{-3} \text{ gm cm}^{-2}$. Best fits are obtained when the chromophores overlie in optically thick cloud layer with an albedo of about 0.8.

(4) "Isotropic Scattering Layer Models for the Red Chromophore on Titan," K. Rages, Icarus, submitted.

A set of atmospheric models containing an isotropic scattering layer under a thin Rayleigh scattering atmosphere has been compared with observations of Titan's geometric albedo and limb darkening at two different wavelengths. Titan's radius to unit optical depth in the visible lies within the range $2600 \text{ km} \leq r \leq 2850 \text{ km}$, the upper half of this range being somewhat more probable than the lower half. The ratio of absorption coefficients $k(0.49 \text{ } \mu\text{m})/k(0.62 \text{ } \mu\text{m}) \geq 2$ for the red chromophore of the presumptive Titanian clouds, which makes it somewhat redder than typical laboratory-produced organic polymers.

(5) "Radiative-Convective Equilibrium Models of the Atmosphere of Titan," K. Hages and Carl Sagan, Icarus, in press.

A set of radiative-convective equilibrium models of Titan's atmosphere are compared with two different sets of observations of the microwave brightness temperatures in an attempt to place limits on the surface temperature. The high frequency observations, if valid, imply a surface pressure $\gg 1$ bar and a massive greenhouse effect. Hydrodynamic calculations suggest that the red chromophore on Titan can reside in the troposphere only if the eddy diffusion rate is very small.

(6) "Temperature Structure and Emergent Flux of the Jovian Planets," Peter Silvaggio and Carl Sagan, Icarus, submitted.

New long path, low temperature, moderate resolution spectra of methane and ammonia, broadened by hydrogen and helium, are used to calculate non-gray model atmospheres for the four jovian planets. Solar energy deposition in the upper atmospheres is of major importance; the fundamental and first overtone of hydrogen contributes enough absorption to create a thermal inversion for each of the planets. A wide range of models of emergent flux, dependent on assumed mixing ratios and scattering by condensates and photochemical organics, is used to calculate the suite of emergent spectral fluxes in the range 600 to $12,000 \text{ cm}^{-1}$ for comparison with the Voyager infrared spectra.

(7) "Occultation of ϵ Geminorum by Mars II. The Structure and Extinction of the Martian Upper Atmosphere," J.L. Elliot, R.G. French, E. Dunham, P.J. Gierasch, J. Veverka, C. Church, and Carl Sagan, Astrophys. J., 217, 661-679.

The occultation of ϵ Geminorum by Mars on April 8, 1976 was observed at three wavelengths and 4 msec time resolution with the 91 cm telescope aboard NASA's G.P. Kuiper Airborne Observatory. Since most of the Earth's atmosphere was below the telescope, scintillation noise in the light curves was greatly reduced from that encountered by ground-based observers. Temperature, pressure and number density profiles of the martian atmosphere were obtained for both the immersion and emersion events. Within the altitude range 50-80 km above the mean surface, the mean temperature is $\sim 145^{\circ}\text{K}$, and the profiles exhibit wave-like structures with a peak-to-peak amplitude of 35°K and a vertical scale of about 20 km. The ratio of the refractivity of the atmosphere at 4500 Å and 7500 Å, determined from the time-shift of the light curves for these wavelengths, is consistent with the atmospheric composition measured by Viking 1, fifteen weeks later. From the "central flash" -- a bright feature in the light curve midway between immersion and emersion -- we find an optical depth at 4500 Å of 3.3 ± 1.7 per km-atm (about 0.23 per equivalent martian airmass) for the atmosphere about 25 km above the mean surface, near the south polar region. This large value and its weak wavelength dependence rule out Rayleigh scattering as the principal cause of the observed extinction.

(8) "Lunar Occultation of Saturn. II. The Normal Reflectances of Rhea, Titan and Iapetus," J.L. Elliot, E.W. Dunham, J. Veverka and J. Goguen, Icarus, in press.

An inversion procedure to obtain the reflectance of the central region of a satellite's disk from lunar occultation data is presented. The scheme assumes that the limb darkening of the satellite depends only on the radial distance from the center of the disk. Given this assumption, normal reflectances that are essentially independent of the limb darkening, and the diameter of the satellite can be derived. The procedure has been applied to our observations of the March 1974 lunar occultations of Tethys, Dione, Rhea, Titan and Iapetus. In the V passband we derive the following normal reflectances: Rhea (0.97 ± 0.20), Titan (0.24 ± 0.03), Iapetus, bright face (0.60 ± 0.14). For Tethys and Dione the values derived have large uncertainties, but are consistent with our result for Rhea.

(9) "Lunar Occultation of Saturn. III. How Big is Iapetus?," J. Veverka, J. Burt, J.L. Elliot, and J. Gougen, Icarus, 33, pp. 301-310.

By considering both the orbital lightcurve of Iapetus and data obtained during the March 30, 1974, occultation of the satellite by the Moon, we obtain information about the brightness distribution on the bright face of Iapetus and derive an accurate value for the satellite's radius. From the observed orbital lightcurve we find that the trailing face of Iapetus must consist predominantly of a single bright material with an effective limb-darkening parameter of $\kappa = 0.62^{+0.10}_{-0.12}$. Given this result the occultation observations imply a radius of 718^{+87}_{-78} km. If the patchy albedo model proposed by Morrison et al. represents the surface of Iapetus accurately (as far as the relative albedo distribution is concerned) then the radius of Iapetus is 724 ± 60 km. Both estimates are consistent with the radiometric radius of 835 (+50, -75) km derived by Morrison et al. Combining our results with the value of $0.60^{+0.14}$ for the normal reflectance (in V) of the material at the center of the bright face derived by Elliot et al. we find that the normal reflectance of the dark side material is $0.11^{+0.04}_{-0.03}$. These values are higher than the corresponding values of 0.35 and 0.05 quoted by Morrison et al.

(10) "Lunar Occultation of Saturn. IV. Astrometric Results From Observations of the Satellites," D.W. Dunham and J.L. Elliot, Icarus, 33, 311-318.

The method of determining local lunar limb slopes, and the consequent time scale needed for diameter studies, from accurate occultation timings at two nearby telescopes is described. The results for the photoelectric observations made at Mauna Kea Observatory during the occultation of Saturn's satellites on March 30, 1974, are discussed. Analysis of all observations of occultations of Saturn's satellites during 1974 indicates possible errors in the ephemerides of Saturn and its satellites.

(11) "Near-Opposition Limb Darkening of Solids of Planetary Interest," J. Veverka, J. Goguen, S. Yang and J. L. Elliot, Icarus, 33, 368-379.

This paper presents a laboratory study of the limb darkening near opposition, of particulate materials of planetary interest and concentrates on the wavelength dependence of this limb darkening. We find that near zero phase the scattering properties of most particulate materials can be described adequately by Minnaert's law. However, there are materials for which such a representation is totally inadequate. Examples are bronzite and graphite, materials that tend to fracture into flakes having mirrorlike surfaces. In addition, there are materials, such as olivine, whose scattering properties within deep absorption bands show definite departures from Minnaert's law at large angles of incidence or emission. Our Minnaert parameters, k and B_0 , were measured at a phase angle of $\alpha = 4^\circ$. For samples of comparable surface texture and roughness, k and B_0 are approximately linearly related, k increasing as B_0 increases.

Very dark materials tend to have $\kappa \approx 0.5$ to 0.6, while very bright materials tend to have $\kappa \approx 1$. The linear relationship between κ and B_0 can be explained in terms of the varying importance of multiple scattering in the surface layer. Thus for materials for which B_0 is strongly wavelength dependent, so is κ . For example, for olivine, κ varies from 0.73 to 0.87 between 0.4 and 1.2 μm . These variations are closely correlated with those in B_0 ; the value of κ is relatively high outside of absorption bands and relatively low within them. For bright materials, κ is very sensitive to surface roughness. For example, for BaSO_4 powder, κ can be changed from ≈ 1.0 to ≈ 0.8 by this effect alone, a fact which has relevance to the photometry of frost-covered satellites. For dark materials, the effects of surface roughness on κ are smaller and more subtle.

(12) "Scattering of Light From Particulate Surfaces. I. A Laboratory Assessment of Multiple-Scattering Effects," J. Veverka, J. Goguen, S. Yang, and J. Elliot, Icarus, 34, 406-414.

A convenient photometric function for many particulate surfaces is the generalization of the Lommel-Seeliger law derived by Hapke (1963) and Irvine (1966). This generalization accounts for the effects of mutual shadowing among particles, but still assumes that multiple scattering within the surface layer can be neglected -- an assumption which is evidently valid for dark surfaces. We describe a series of laboratory measurements which test the range of validity of this basic assumption, and the applicability of the Hapke-Irvine photometric function, for particulate surfaces whose normal reflectances range

from 0.04 to 1.04. We find that multiple-scattering effects can be neglected, and that the Hapke-Irvine function can be used, for particulate surfaces whose normal reflectance is about 0.3 or less. The function is definitely inapplicable to surfaces whose normal reflectance exceeds 0.4.

(13) "How to Compare the Surface of Io to Laboratory Samples," J. Veverka, J. Goguen, S. Yang, and J.L. Elliot, Icarus, 34, 63-67.

Since one does not know the photometric functions of various parts of Io, one cannot convert the observed geometric albedo of the satellite to a parameter more directly measurable in the laboratory. One must therefore convert laboratory reflectances to geometric albedos before quantitative comparisons between Io's surface and a laboratory sample are made. This procedure involves determining the wavelength dependence of the sample's photometric function. For substances such as sulfur, whose reflectance varies strongly with wavelength, it is incorrect to assume that the photometric function, and hence the ratio (laboratory reflectance/geometric albedo) is independent of wavelength. To illustrate this point, measurements of the color dependence of this ratio for sulfur are presented for the specific case in which the measured laboratory reflectance is the sample's normal reflectance. In general, unless the laboratory reflectance is precisely the geometric albedo, a wavelength-dependent correction factor must be determined before the laboratory sample can be compared quantitatively with Io's surface.

(14) "On Matching the Spectrum of Io: Variations in the Photometric Properties of Sulfur-Containing Mixtures," J. Veverka, J. Goguen, S. Yang, and J. Elliot, Icarus, in press.

The problem of comparing laboratory spectra of sulfur-containing binary mixtures with the spectrum of Io is discussed. For the satellite, the observable is the geometric albedo as a function of wavelength, whereas in the laboratory one often measures some other type of albedo. In a previous paper we demonstrated that for pure sulfur the multiplicative factor which converts the laboratory albedos to geometric albedos can be strongly wavelength dependent. The present paper demonstrates that this is also true for binary sulfur-containing mixtures. Furthermore, there is no universal conversion factor applicable to all binary mixtures; nor can the factor be interpolated for a particular mixture from the conversion factors of the two end members. The conversion factor is a function not only of the specific composition of a binary mixture, but of the relative particle size distributions of the two components, and must be measured specifically for each individual sample if a quantitative comparison between a laboratory sample and Io's surface is desired.

During the past year the principal investigator was the recipient of the Pulitzer Prize for non-fiction; the NASA Medal for Distinguished Public Service; and, with many co-workers, the Newcomb Cleveland Prize of the American Association for the Advancement of Science. He received honorary doctoral degrees from the University of Wyoming, Clark University,

and Whittier College; was elected President-elect of the Planetology Section of the American Geophysical Union; and continued as Chairman of the Study Group on Machine Intelligence and Robotics at NASA Headquarters, as a National Director of the American Astronautical Society, as a member of the Council of the Federation of American Scientists; and as a member of the Fellowship Panel of the John S. Guggenheim Memorial Foundation. He was also elected an honorary member of Phi Beta Kappa and a Fellow of the American Academy of Arts and Sciences. He served as Stahl Lecturer at Bowdoin College, Johnson Lecturer at Penn State, Christmas Lecturer at the Royal Institution in London, Menninger Lecturer for the American Psychiatric Association and Damon Lecturer for the National Science Teachers Association.